Advanced Linkages Between Power Flow and Production Cost Modelling

ESIG Tutorial: Integrating Planning Tools and Processes for Effective Planning of Future Power Systems

March 2023
GEEnergyConsulting.com

GE Energy Consulting

GE Energy Consulting: GE's grid experts for >100 years

GE EXPERTS, OEM AGNOSTIC

~130 grid experts
9 countries
>100 patents

GENERATION INTEGRATION | voltage & frequency performance

- Interconnection support
- Grid code testing and compliance

TRANSMISSION STRATEGY | complex plant interconnection

- Stability studies
- Network risk assessment
- Grid reinforcements

ECONOMIC ANALYSIS | grid value of technology

$$

- Renewables planning and strategy
- Financial modeling and forecasting

Transients milliseconds ↔ **Planning** years

Models

Software

Power flow GE PSLF*

Energy GE MAPS*

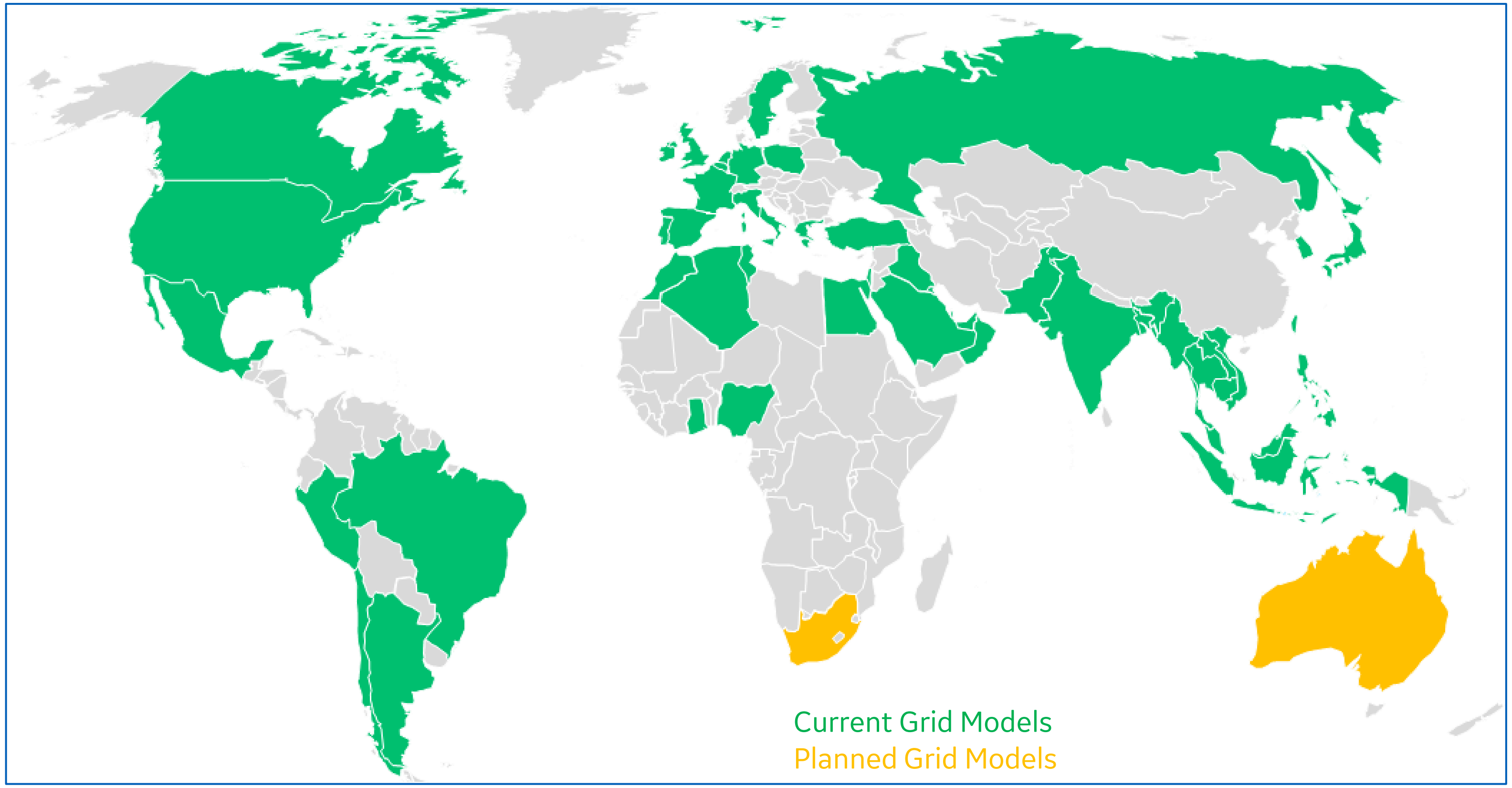
Capacity GE MARS*

GE technology
1/3 earth's power | #1 clean energy fleet

*Trademark of General Electric

GE Energy Consulting models grids **across the globe**

40 COUNTRIES ... 5 CONTINENTS



Economics + Physics
Transmission constrained + least cost dispatch to serve load

High resolution
Hourly in time ... nodal/zonal in space

Forward-looking
20 year forecast ... transmission, generation + historical validation

Top technologies
Leading generation types independent of manufacturer

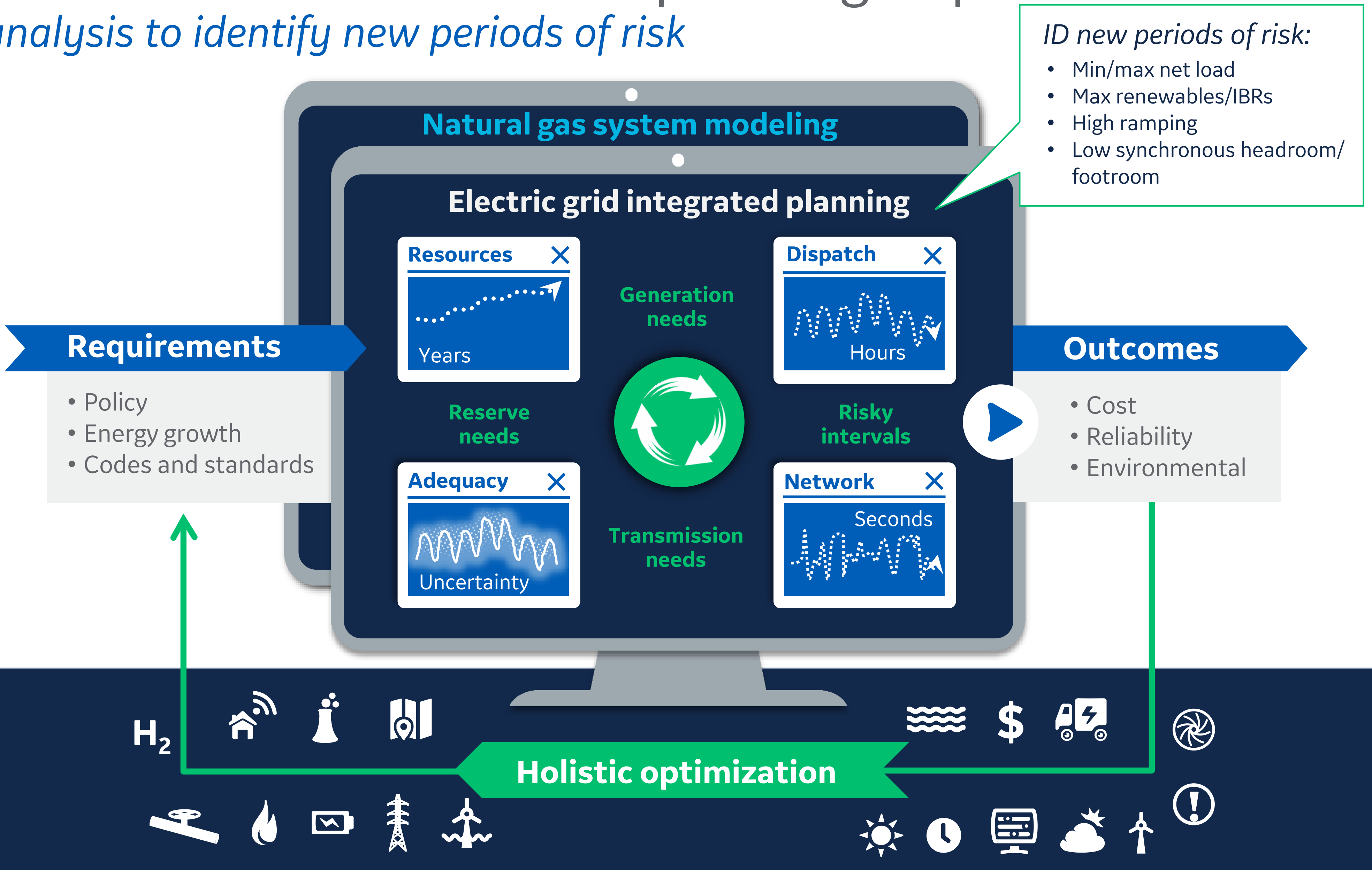
North America: Canada, US, Mexico • **Europe:** UK, Ireland, Spain, Portugal, France, Italy, Luxemburg, Belgium, Netherlands, Germany, Poland, Russia, Sweden, Greece, Turkey • **South America:** Chile, Argentina, Peru, Brazil • **Africa:** Morocco, Algeria, Tunisia, Egypt, Ghana, Nigeria • **Middle East:** Saudi Arabia, Bahrain, Qatar, UAE, Oman, Kuwait, Iraq, Israel • **Asia:** India, Bangladesh, Pakistan, Myanmar, Thailand, Vietnam, Laos, Cambodia, Philippines, Malaysia, Singapore, Indonesia, Brunei, Taiwan, Japan, S. Korea

Driving insightful client decisions: costs -> revenues, planning -> operations

Increasing Complexity of Grid Modelling

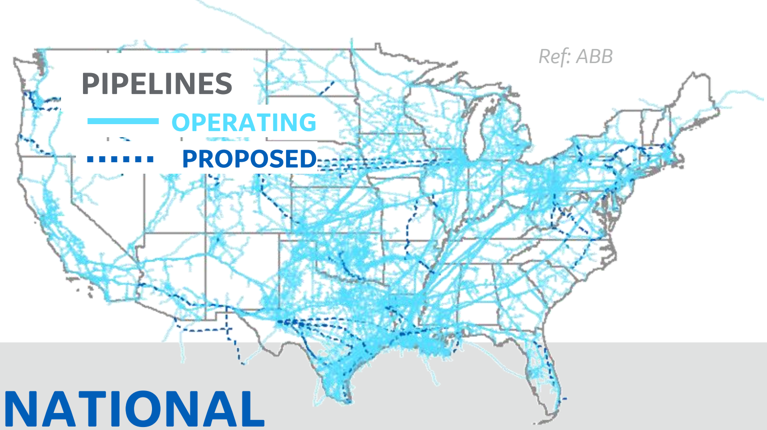
Deep decarbonization … Holistic planning required

Hourly analysis to identify new periods of risk



Are there risks to gas supply as we decarbonize?

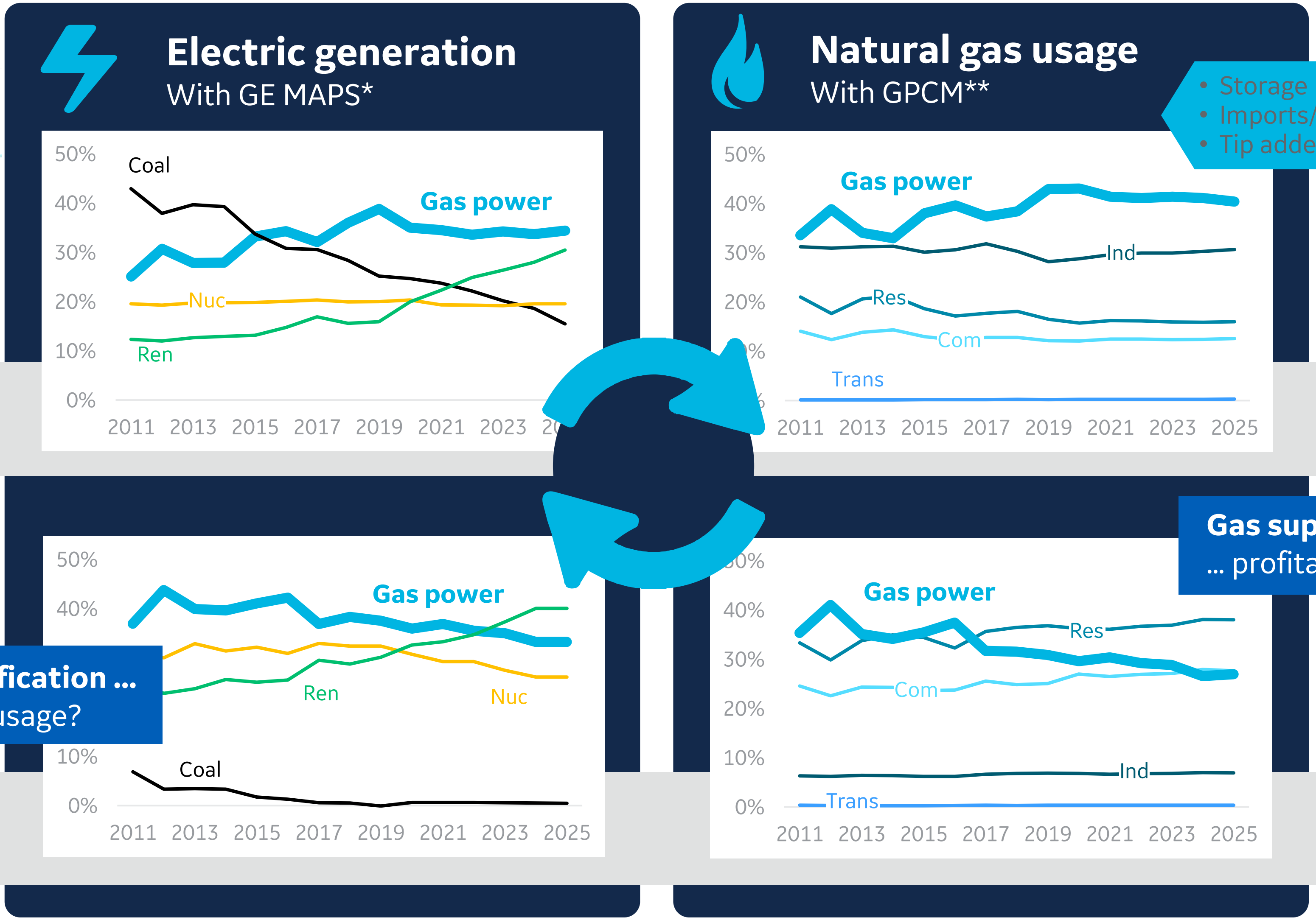
Cross-sector insight required to identify reliability needs



NATIONAL

New pipelines
... justified?

REGIONAL
(e.g. NY)



Electrification ...
↑ gas usage?

Gas suppliers
... profitable?

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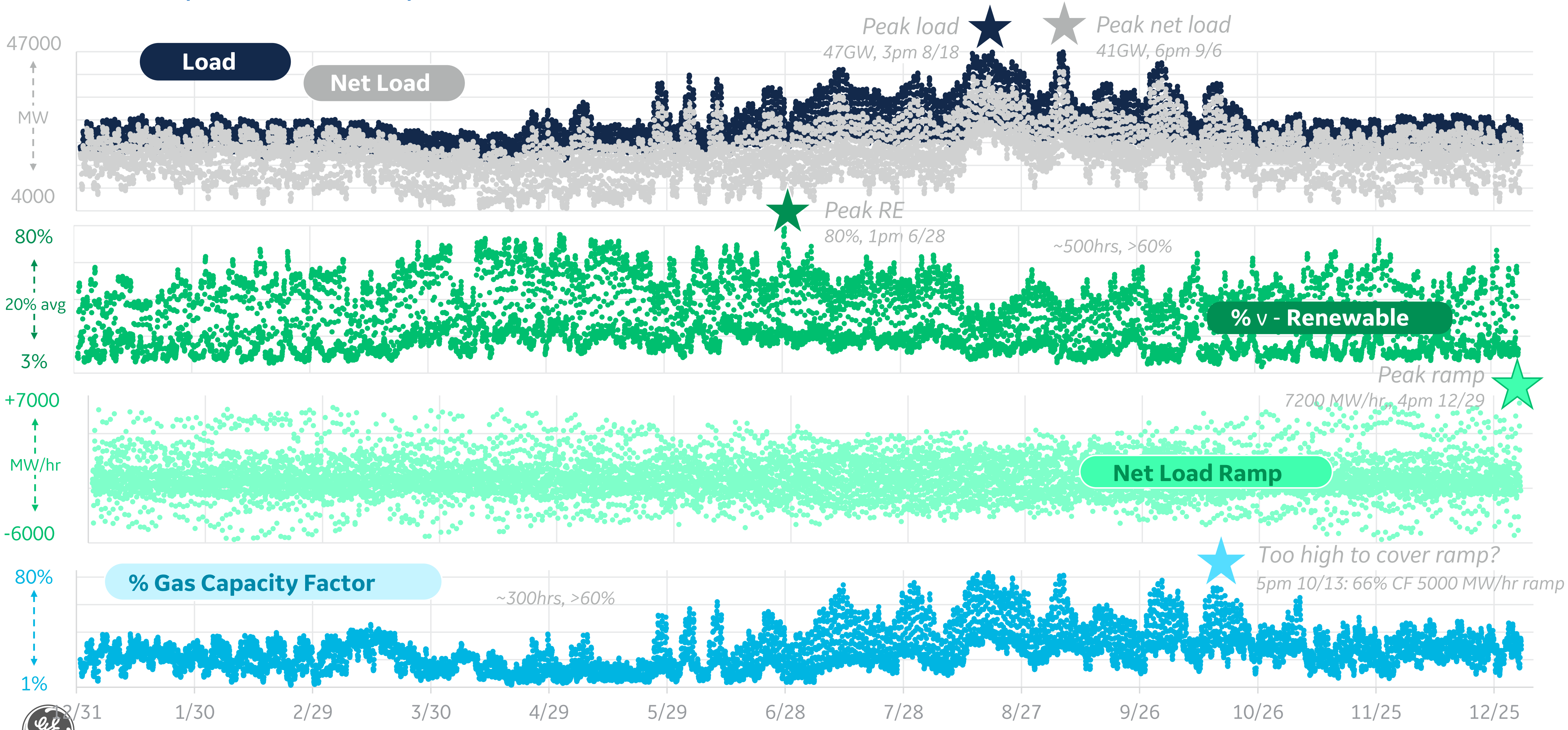
**GPCM is a registered trademark of RBAC, Inc.

Ref: EIA STEO 2020, AEO 2020 outlook, GPCM , MAPS

Even at ~20% average wind + solar, California sees hours at 80%!

New non-peak hours of risk



...tyx ABB, RE generation from CAISO

Grid reliability is maintained across multiple timescales

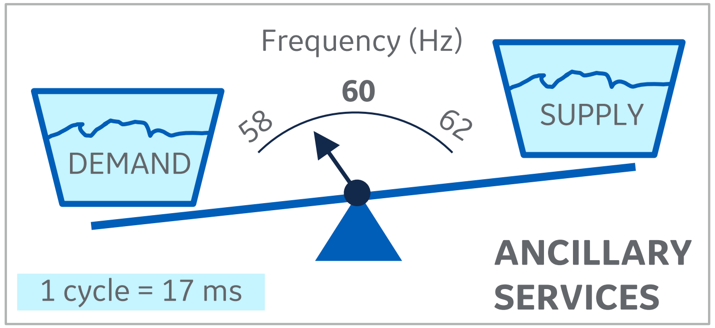
Planning tools reflect similar timescales

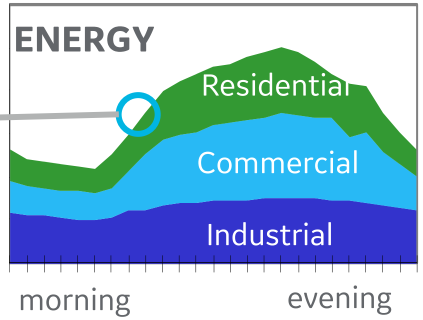
PHYSICS

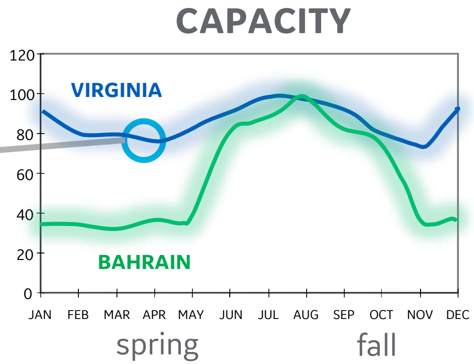
... maintain frequency & voltage

BALANCING

... deliver enough power to meet demand







← SECONDS — HOURS — YEARS →

https://www.nerc.com/pa/rrm/ea/Pages/Major-Event-Reports.aspx
https://www.aer.gov.au/wholesale-markets/compliance-reporting/investigation-report-into-south-australias-2016-state-wide-blackout

EVALUATING NETWORK RISKS

NETWORK RISKS → ASSESSMENT → NEEDS → IMPLEMENTATION

Large signal disturbances: Frequency stability, Voltage stability, Weak grid

Small signal: Transient stability, Small signal stability

NETWORK RISKS	LOAD FLOW	DYNAMICS	TRANSIENTS	OTHER	NEEDS	DISPATCH DEPENDENT	MECHANISM	GENERATION: SYNCHRONOUS	GENERATION: INVERTER
STEADY STATE Normal and outages	✓				❑ Transmission adequacy	✓	Network upgrades	Shifting mix influences direction and timing of power flows and thermal limit risks	
FREQUENCY STABILITY Steady state and disturbances	✓ ⟳	✓			❑ Inertia and fast frequency response	✗	Grid codes Ancillary services	Inherent to machine	Via converter controls
					❑ Primary response (governor)	✓	Grid codes	No opportunity cost	Pre-curtailment req'd. … non-zero cost
VOLTAGE STABILITY Steady state and disturbances	✓ ⟳	✓ ⟳	✓		❑ Voltage control	✗	Grid codes Interconnect approval	Via excitation & rotational physics	Via converter controls
					❑ Reactive power	✗			
WEAK GRID Control stability		✓ ⟳	✓ ⟳	Short circuit analysis	❑ Voltage source	✗	Grid codes Interconnect approval	Via short circuit current	Via grid-forming controls
TRANSIENT STABILITY Angular stability … rotor and system		✓ →	✓		❑ Transmission adequacy	✓	Network upgrades	Critical clearing time	Phase-locked loop (traditional)
SMALL SIGNAL STABILITY Power swings and sub synchronous resonance (SSR)			✓	Frequency domain and Bode analysis	❑ Power swing damping	✓	Grid codes	Power system stabilizer (PSS)	Power oscillation damping
					❑ SSR damping	✓	Interconnect approval	TSR (SSR/SSTI)	Active damping controls for (SSR/SSCI)

Three main flavors of grid stability assessment

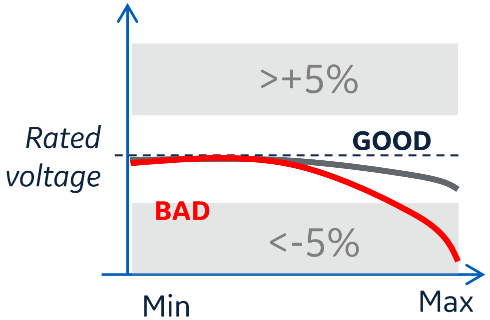
e.g. New project interconnection study

Violations can result in upgrade costs, denied interconnection, curtailment

LOAD FLOWS

Under **static** conditions, are power & voltage limits violated?

Static dispatch condition



Vary the power output of new project

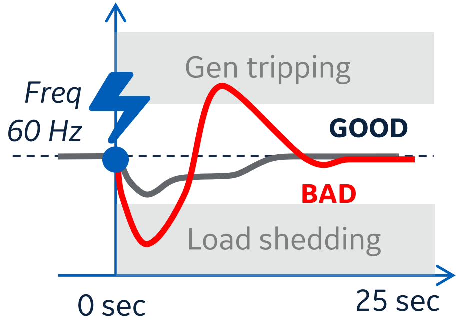
e.g. Summer peak

- High load
- High gen output
- High solar, low wind
- N-0, N-X

DYNAMICS

After a **disturbance** does the system blackout?

Add grid disturbance



Time after disturbance

e.g. Trip largest unit

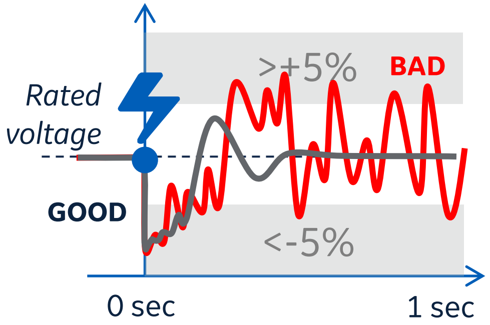
- Nine mile point 2

TRANSIENTS

(optional today)

After a **disturbance w/ high inverter** penetration, do controls get confused?

High res: millisec + IBR ctrls



Time after disturbance

e.g. Trip largest unit w/ high IBRs:

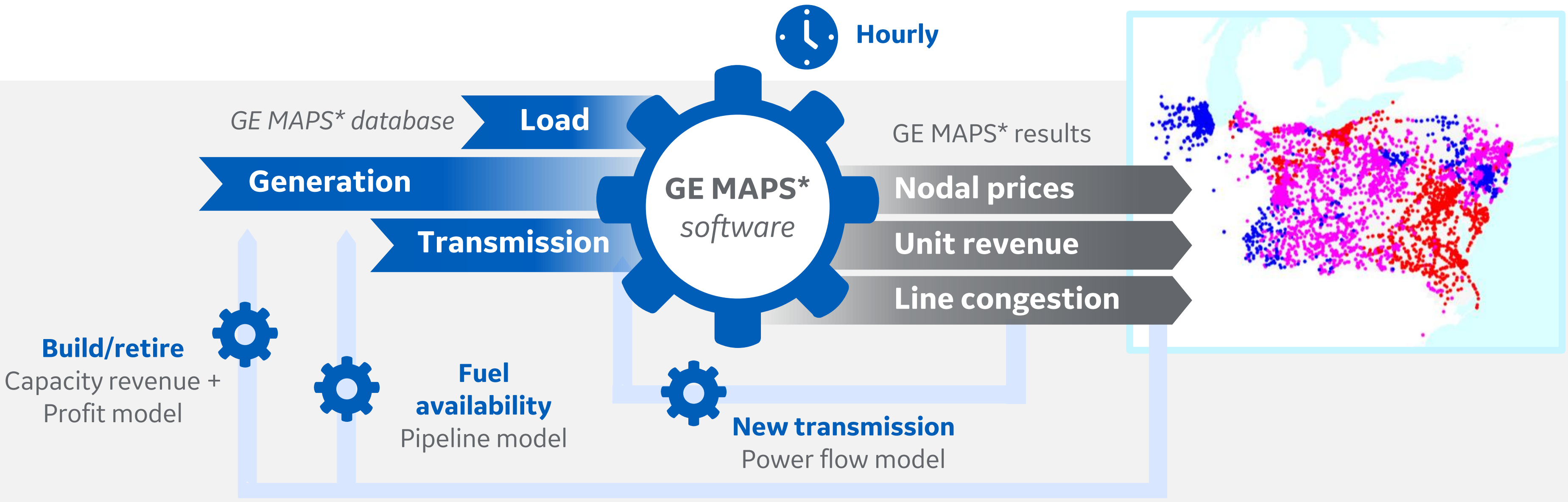
- Wind
- Solar
- HVDC
- Batteries

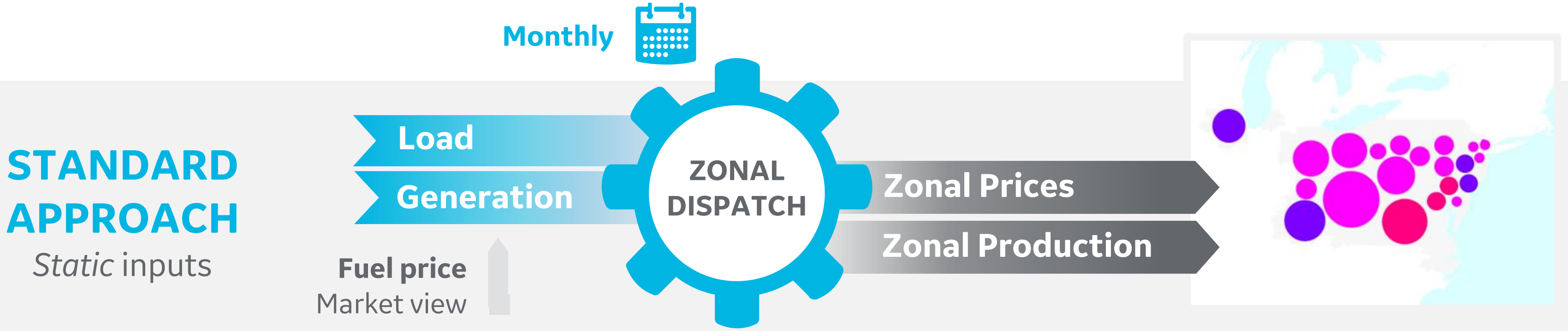
SOFTWARE ← Siemens PSS/e*, GE PSLF, Digsilent Power factory → ← PSCAD*, windTRAP, ATP EMTP-RV →

GE MAPS* Production Cost Modelling

*Trademark of General Electric

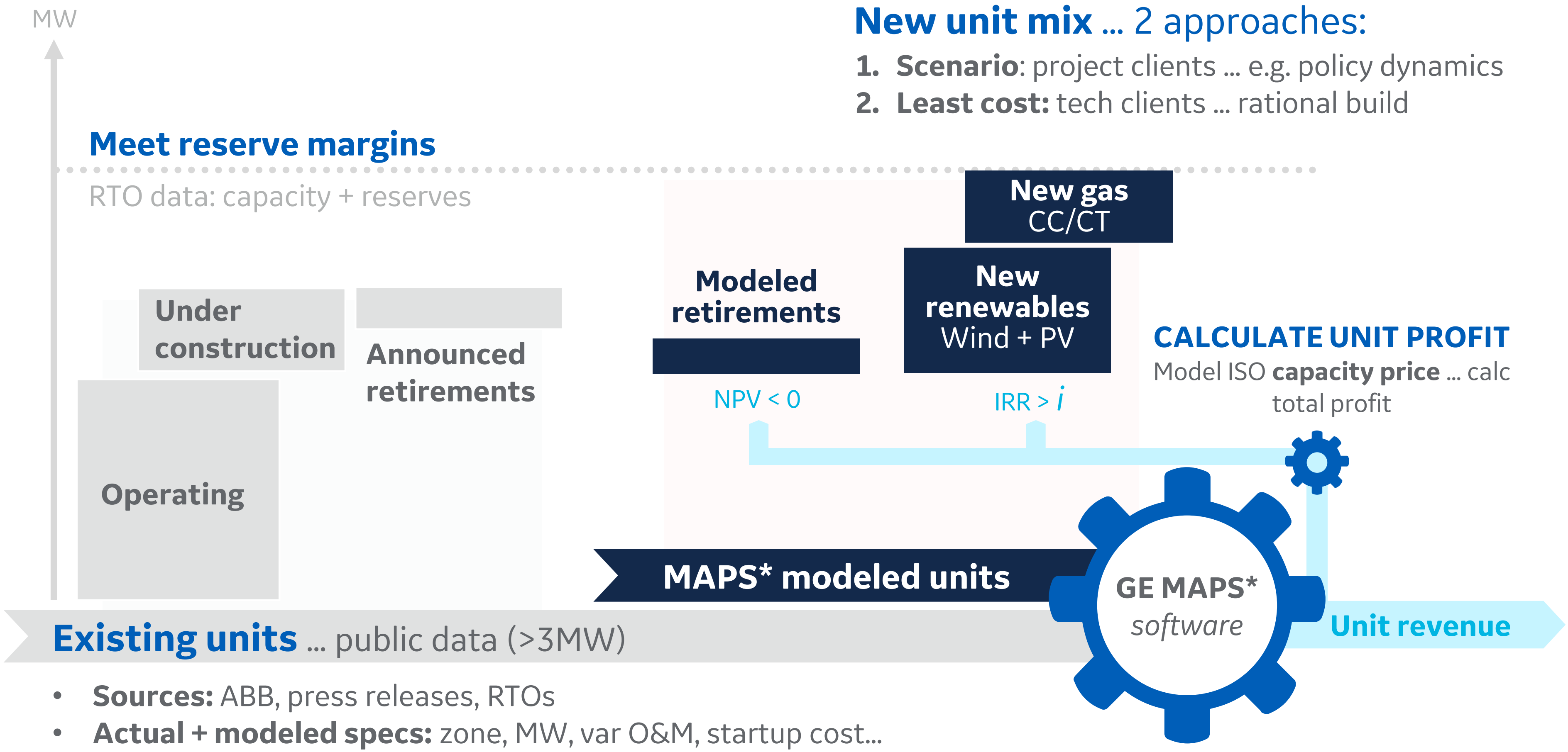
GE MAPS*: An **iterative + integrated** approach to energy market simulation





GE MAPS* database: Generators

ITERATIVE *APPROACH … BUILD/RETIRE TO MEET RESERVE MARGINS & UNIT PROFITABILITY*



- **Sources:** ABB, press releases, RTOs
- **Actual + modeled specs:** zone, MW, var O&M, startup cost…

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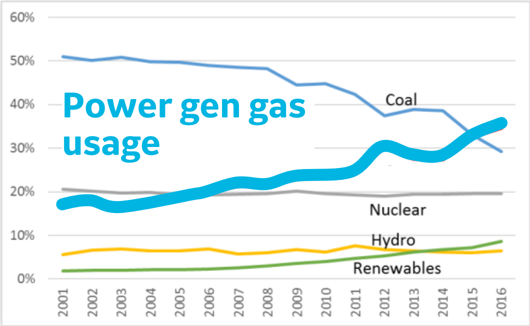
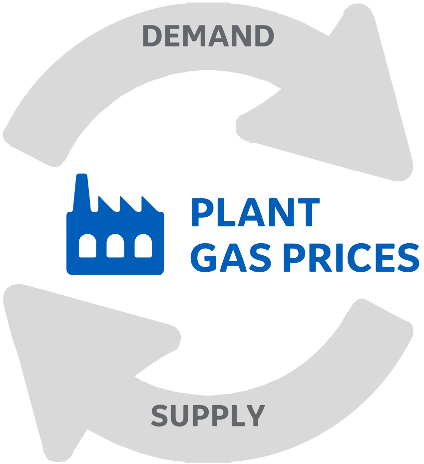
GE MAPS* database: Gas price forecast

PLANT-LEVEL PRICES VIA ELECTRICITY + GAS MARKET MODELING

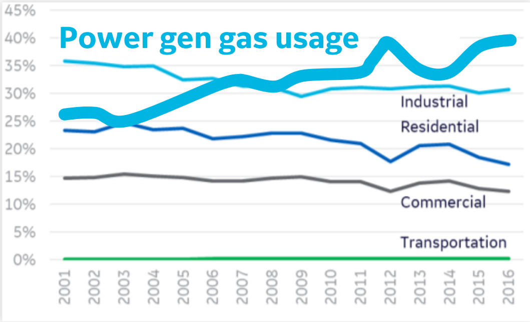
Electricity market modeling
with GE MAPS





Natural gas market modeling
with GPCM**

- Pipelines
- Storage
- Im/Export
- Tip adders



GE MAPS database
fundamentals-based

Simulated: GE MAPS + GPCM models

Hub price

Hub + transport … ESP in congested areas

Plant price
"burner tip"

Std approach …
market-based

NYMEX futures … limited past 10 year views

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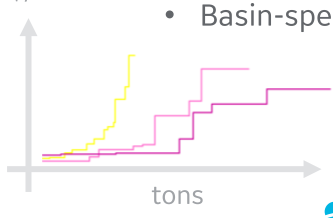
GE MAPS* database: Coal & oil price forecast

Coal price forecast ... price elastic

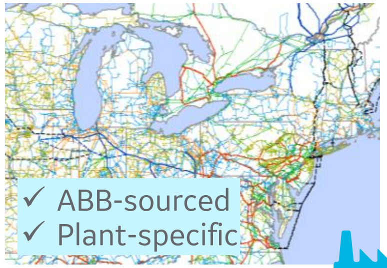
Supply curve

- EPA-sourced
- Basin-specific



Basin price

Transport adder



✓ ABB-sourced
✓ Plant-specific

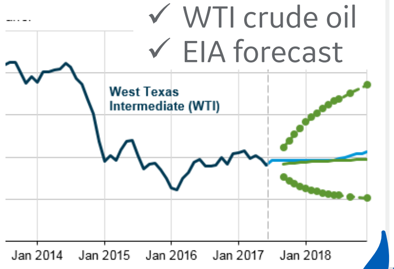
Delivered price

price
demand

Oil price forecast ... varies by product

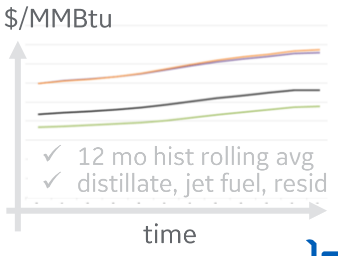
Price forecast

✓ WTI crude oil
✓ EIA forecast



Crude price

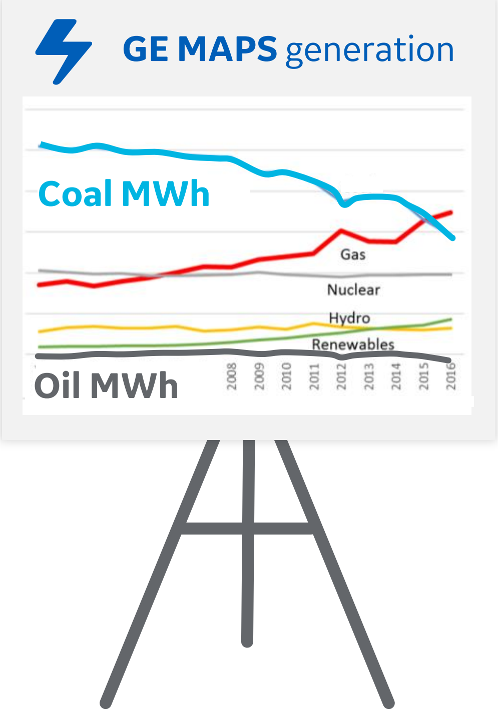
Refined ratio



✓ 12 mo hist rolling avg
✓ distillate, jet fuel, resid

Refined price

price



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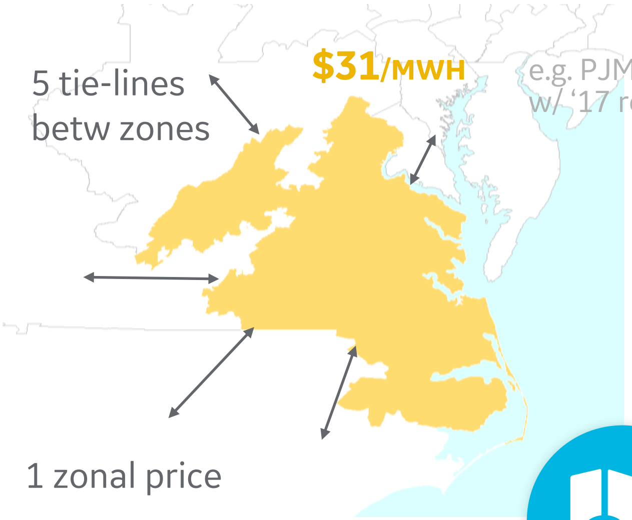
GE MAPS* database: Transmission model

TRANSMISSION CAN HAVE A SIGNIFICANT INFLUENCE ON PRICE

Standard approach: **Zonal** model



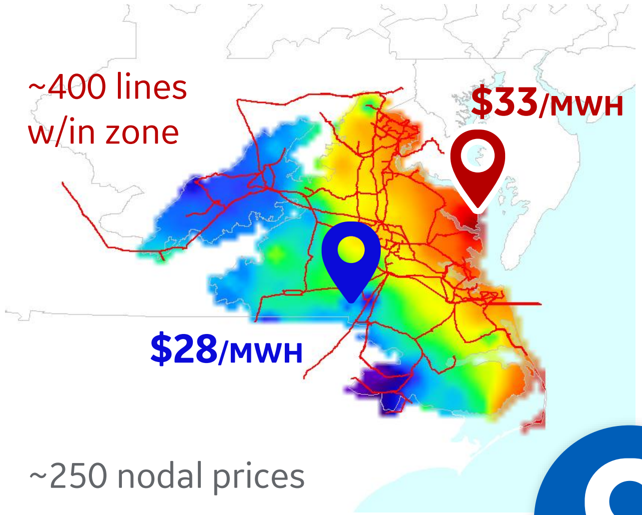
1 zonal price

~200 MB Typical 20 yr simulation (PJM, Eastern interconnection)

Power flows **between** zones

ZONAL price scenarios

GE MAPS approach: **Nodal** model



~250 nodal prices

~2,000,000 MB

Power flows **within &** **between** zones

NODAL price scenarios

* Trademark of General Electric

GE MAPS* database: **Transmission model**

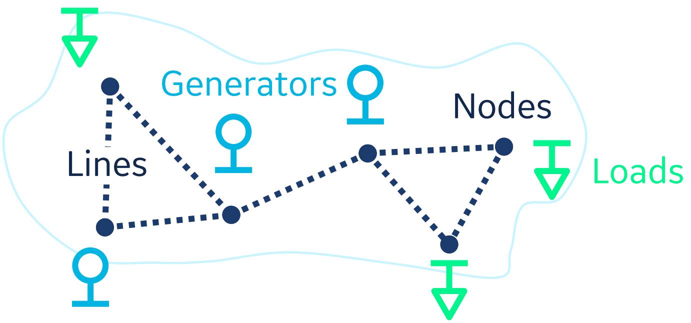
BRINGING PHYSICS INTO FINANCIAL MODELING

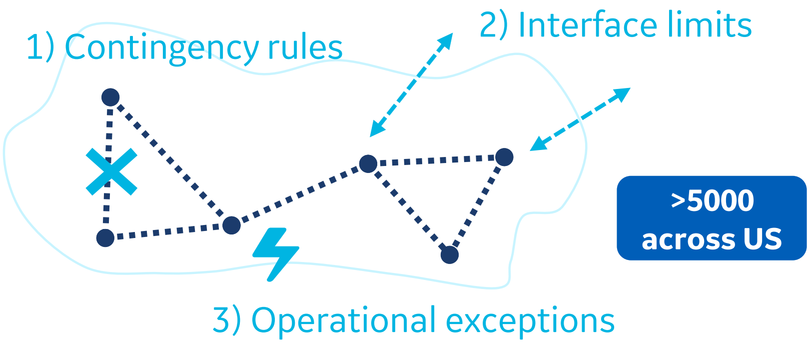
The electrical network

The ideal grid: how the circuit directs power

Operational constraints

The real grid: reliability rules/exceptions





RTO-sourced: annual update, CEII access req'd
Four main elements: gen, loads, nodes, lines … GE PSLF* model
Specs: Node #'s, MW ratings, impedances

GE intel: decades of RTO research, NDAs req'd

1) **Contingencies:** grid balance w/ outages (N-1)
2) **Interface limits** across multiple lines (MW & V)
3) **Operational exceptions:** Must-run units, underground line exceptions, local req'ts

* Trademark of General Electric

Round Trip modelling

Round-Trip Modeling

A common round-trip model is to feed the generation dispatch from a production cost model into a power flow (PSSE or PSLF) model.

- ✓ Why go through this process?
- ✓ Why not just run each model separately?

Typically, the PSSE or PSLF model is of a max or min load case. These cases are estimates of generation levels to match a max and min load event. However, the generation is not based on an economic dispatch.

- ✓ Using the production cost model to effectively dispatch generation, and to be able to choose the right time period to be represented in the power flow (other than a min or max load case), like high renewables case, is often more relevant for most studies.

Another reason for round trip modelling, is to align the models to the same assumptions or starting point. For example a production cost and reliability study may require aligning the models assumptions before starting the study.

Inter-model setup

The key to most model inputs and outputs is having a consistent database, particularly generators.

Using the same generator naming convention is ideal.

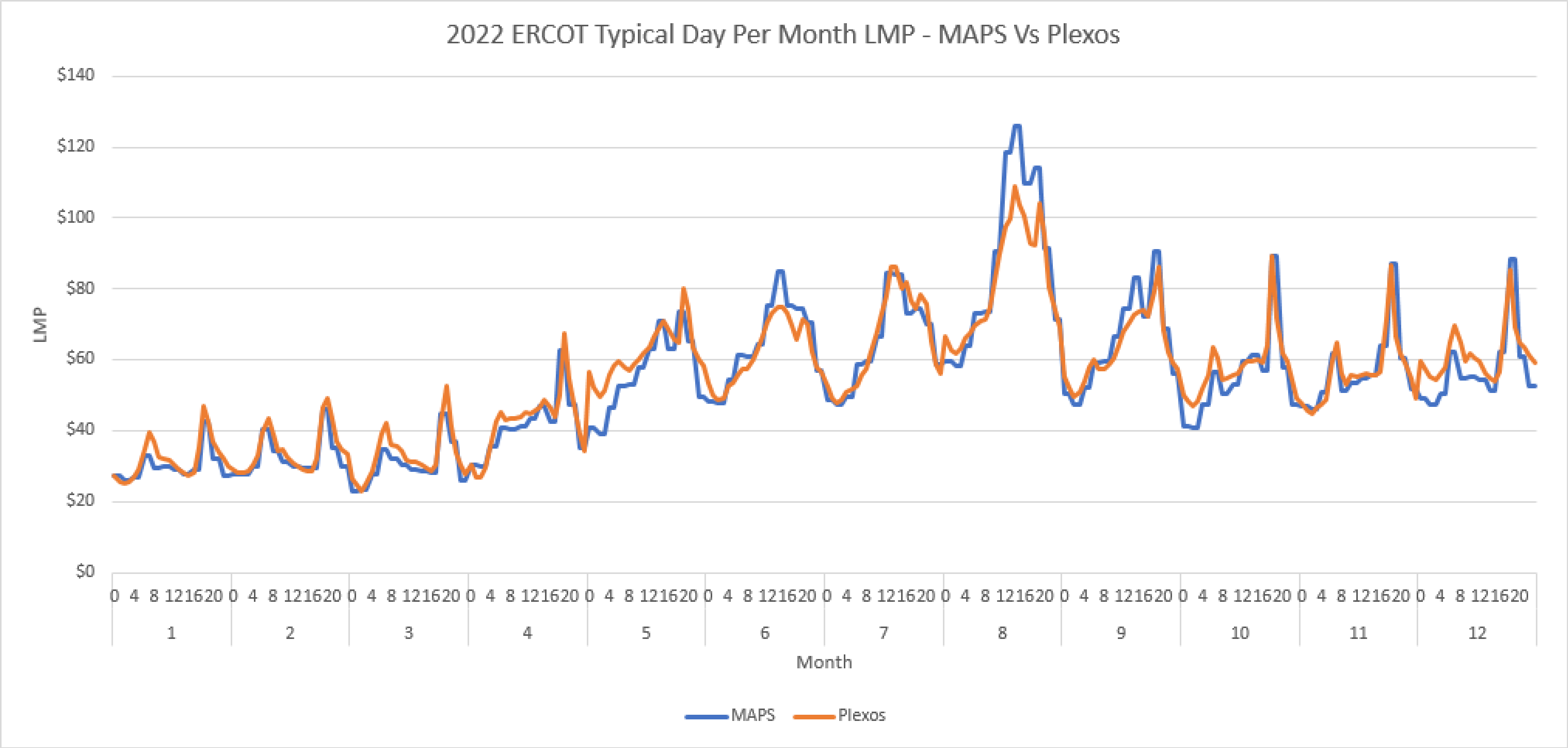
- ✓ This can often be difficult or non-existent for established databases where the names are already established.

The next best thing is having a unique generator identifier, like EIA generator number, for both datasets. Other alternatives (particularly for overseas models) is PLATTS UDI generator number.

- ✓ Then the inputs and outputs can be lined up without too much trouble.

Some software allow imports / exports from other products.

- ✓ PLEXOS has an import feature of PSSE load flow cases for example. The naming convention will default to the parent database (e.g. PSSE).



have been
want to be
k both models
outputs or
ther as well
arty dataset

Benchmarking example above of ERCOT between production cost models GE MAPS and PLEXOS for 2022.

- ✓ Benchmarking will help validate the accuracy of the models.
- ✓ Benchmarking can be done relative to historical data or a back-cast where a model is run for a historical year and compared to historical results (LMP, generation, or other relevant metrics).

Sharing of Results

Ideally, the best way to share results between models would be to have a common output file like a .csv file or similar that could then be used as an input into the subsequent step of modelling.

Alternatively, build a template from which one could wholesale copy the results from one model and paste into the second.

- ✓ Sometimes this require a bit of trial and error and is initially a manual process.
- ✓ However, if this is likely to be a common approach, then would be beneficial for ways to automate the exchange of data with the use of python or an API.
- ✓ For example, ECG has built a script to take regular updates from our North American GE MAPS* databases and automatically update inputs into our PLEXOS database (for capacity expansion or specific studies requiring that software).

Case Study

Value and Role of Pumped Storage Hydropower under High Variable Renewables

Chrissy Bisceglia
Senior Engineer
GE Energy Consulting

VALUATION OBJECTIVES

EVALUATE AND UNLOCK FULL POTENTIAL OF PSH TO SUPPORT GRID OPERATIONS, STABILITY & RESILIENCY

Overcome market barriers and enable PSH technology deployment for utilities, Public Utility Commissions (PUCs), developers and regional planners

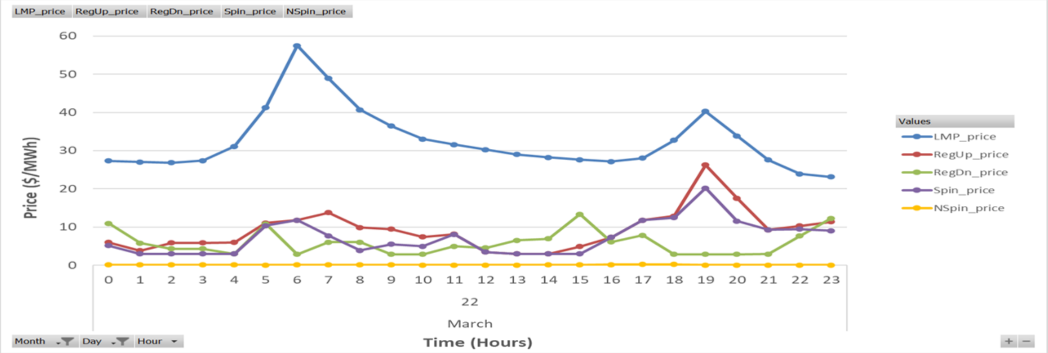
- Develop a **PSH scheduling tool** to co-optimize energy and ancillary services, considering price elasticity in the power market
- Analyze and quantify the **potential value of PSH** under different system conditions
- Develop a set of **Variable Speed PSH stability models** for transmission planners to study the impact of PSH on the grid
- Investigate the dynamic **stability capability of VSPSH** and assess its impact on grid frequency response and transient stability
- Investigate the **PSH contribution to resource adequacy**

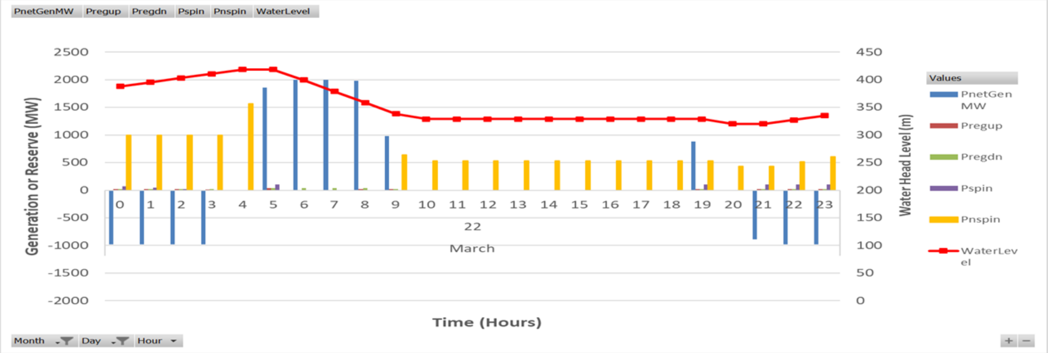
PSH SCHEDULING TOOL

Goals: Maximize PSH operating profit on a given optimization horizon while respecting operational and scheduling constraints and enabling PSH developers and owners to unlock PSH value from both ancillary services and energy.

- A novel PSH Scheduling tool was developed, incorporating for the first time the impact of variable height differences between reservoirs ('head') and variable speed machine behavior.
- The tool is run in conjunction with a production cost optimization tool to allow for price elasticity effects to be captured.
- Developed in Python open source software and can be easily modified to meet future needs.

CAISO Market Prices for March 22, 2018

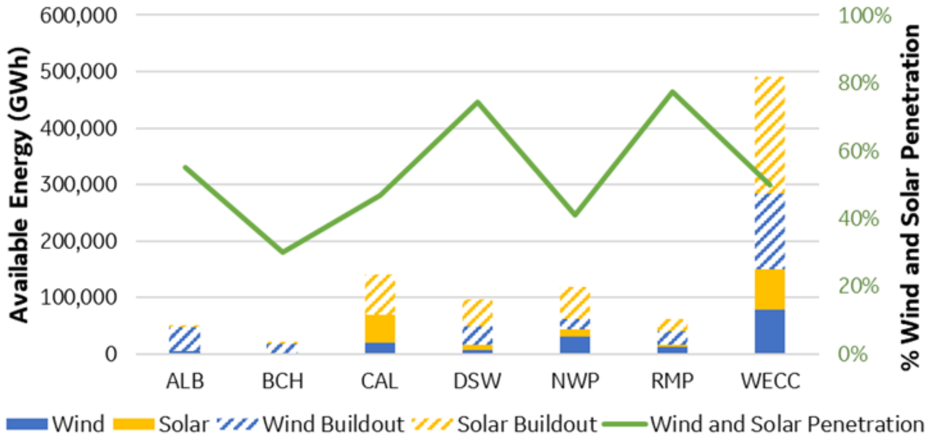


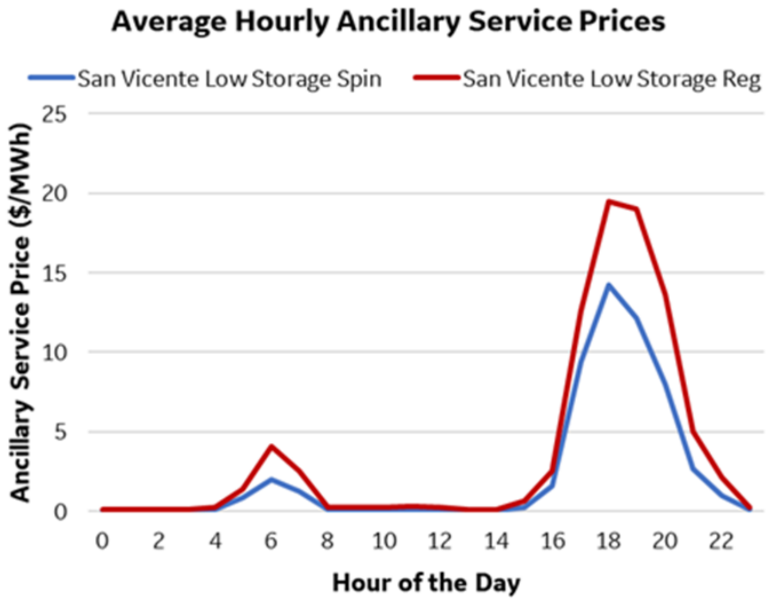


PSH optimal dispatch

PRODUCTION COST MODELING: Base Assumptions

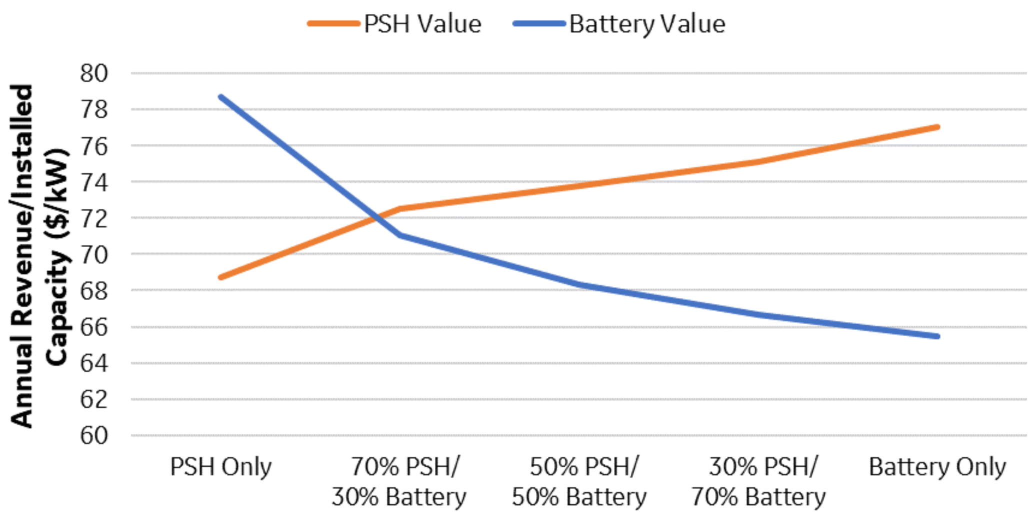
- GE non-proprietary WECC database 2028 study year with 50% renewable penetration
- Economic retirement analysis performed after the renewable additions.
- Simple transmission expansion exercise to alleviate congestion due to generic renewable buildout.
- The base case, referred to as “low storage”, includes some PSH and battery storage (8 TWh of PSH, 3 TWh of battery)
- Ancillary service modeling:
  - CAISO 2017-2018 IRP production cost model requirements for regulation and spinning reserve
  - GE MAPS calculates hourly total ancillary service price
  - Historical CAISO prices used to determine how much of the total price for each ancillary product

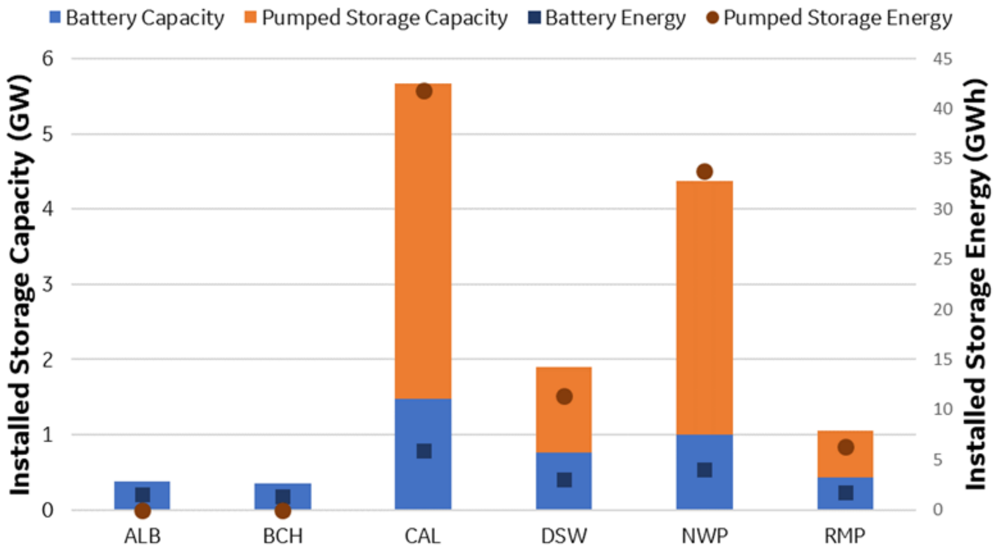




PRODUCTION COST MODELING: High Storage Scenario

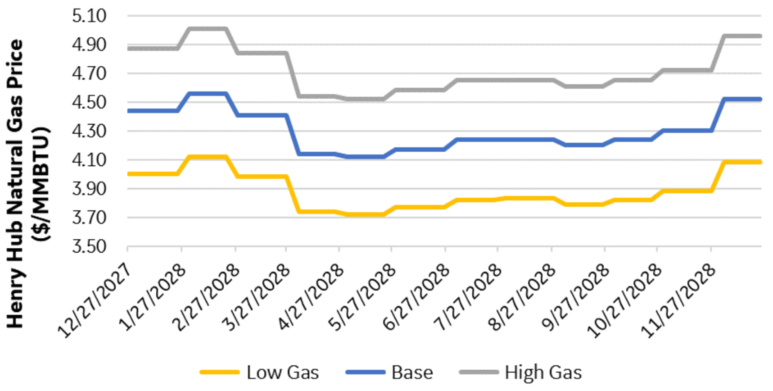
- High Storage scenario developed to understand the value of PSH with more storage competition.
- A storage value metric (Annual Revenue $/Installed Capacity kW) was used to determine when the system begins to be saturated (a 25% decrease was chosen as the “saturation point” for this study)
- When PSH or Battery technologies were added alone, the value metric decreased by 25% when approximately 14 GW were installed.
- Various mixes of PSH and Battery technology were calculated and a 70% PSH (9.8GW, 98GWh) and 30% Battery (4.2 GW, 16.8 GWh) scenario was selected



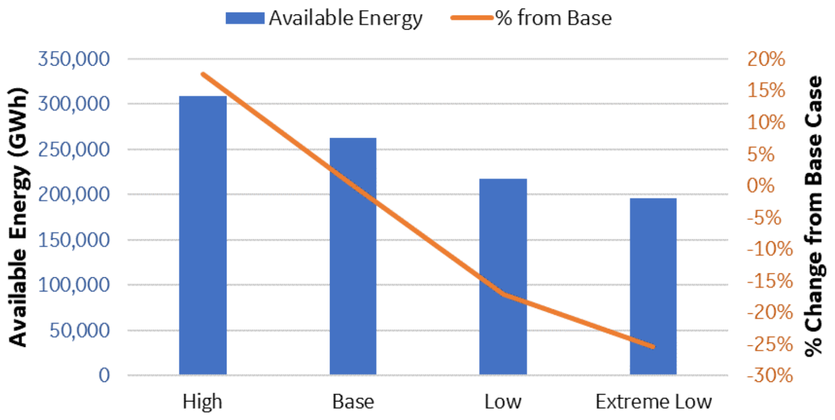


PRODUCTION COST MODELING: Cases & Outputs

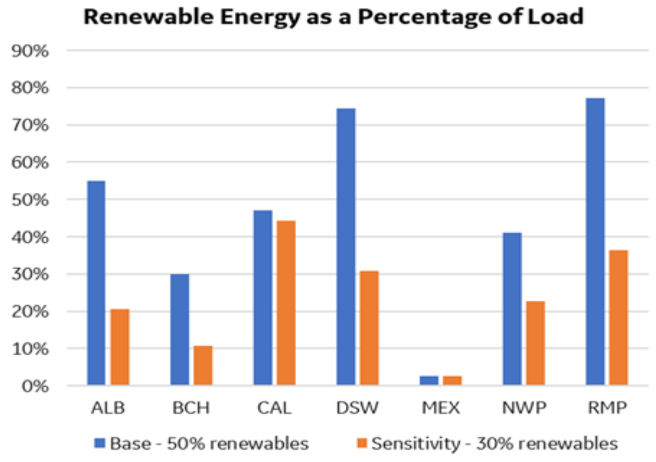
Natural Gas Sensitivities



Hydro Sensitivities



30% Renewable Penetration

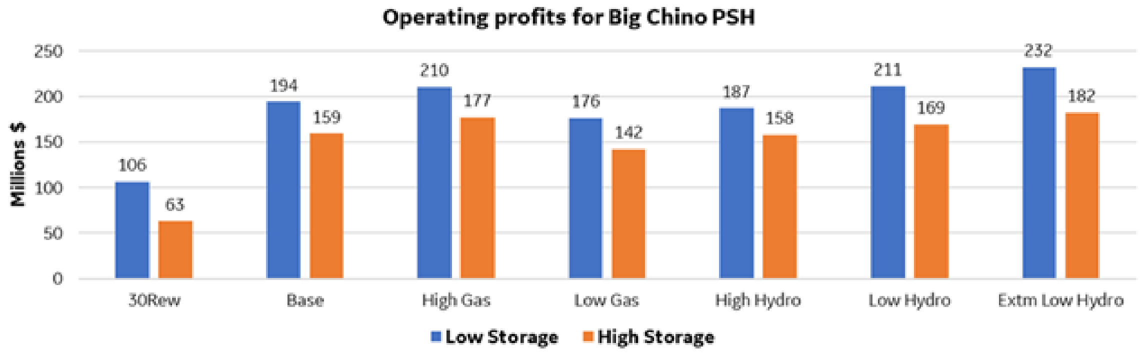


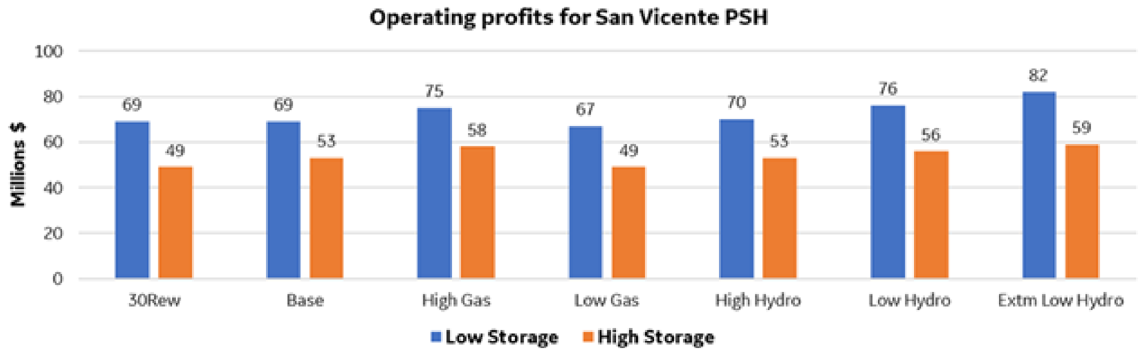
- Total of 42 cases, low and high storage scenarios with base case and 6 sensitivities
- The PSH plant schedules were revenue-optimized using the scheduling tool developed by GE Global Research.
- Results analyzed for both WECC-wide system impact and individual plant revenue

	Big Chino	San Vicente
Capacity (MW)	2,000	500
Duration(hrs)/ Energy (MWh)	10/20,000	8/4,000
Location	AZ	CA
Revenue Streams	Energy	Energy & Ancillary Services

PRODUCTION COST MODELING: Results

Delta From Case without Units	Production Cost ($/M)		CO2 Emissions (million tons)		Simple Cycle Peaker Cycling		Curtailment (GWh)	
	W/ Big Chino	W/ San Vicente	W/ Big Chino	W/ San Vicente	W/ Big Chino	W/ San Vicente	W/ Big Chino	W/ San Vicente
Base Low Storage	-182	-62	-1.82	-0.5	-4,762	-1,572	-4,753	-1,102
30% Renewables Low Storage	-93	-46	-0.15	-0.24	-5,936	-2,137	-1,406	-550
High Gas Price Low Storage	-194	-61	-1.72	-0.46	-4,587	-1,337	-4,790	-1,102
Low Gas Price Low Storage	-164	-56	-1.73	-0.43	-4,752	-1,625	-4,666	-1,114
High Hydro Low Storage	-184	-56	-1.68	-0.41	-5,676	-1,860	-4,811	-1,115
Low Hydro Low Storage	-195	-62	-1.62	-0.45	-5,387	-2,429	-4,399	-1,028
Extreme Low Hydro Low Storage	-202	-64	-1.55	-0.42	-4,820	-2,182	-4,324	-1,032
Base High Storage	-167	-48	-1.65	-0.39	-4,461	-2,132	-4,189	-806
30% Renewables High Storage	-58	-28	0.02	-0.07	-3,664	-2,637	-737	-278
High Gas Price High Storage	-181	-51	-1.74	-0.44	-4,707	-1,660	-4,312	-845
Low Gas Price High Storage	-143	-34	-1.74	-0.27	-3,023	-371	-4,274	-733
High Hydro High Storage	-165	-36	-1.71	-0.33	-5,073	-1,851	-4,412	-834
Low Hydro High Storage	-181	-48	-1.76	-0.29	-5,793	-1,700	-4,038	-772
Extreme Low Hydro High Storage	-184	-50	-1.7	-0.39	-5,302	-2,143	-4,118	-863





Positive system impact in all scenarios, no clear winner.

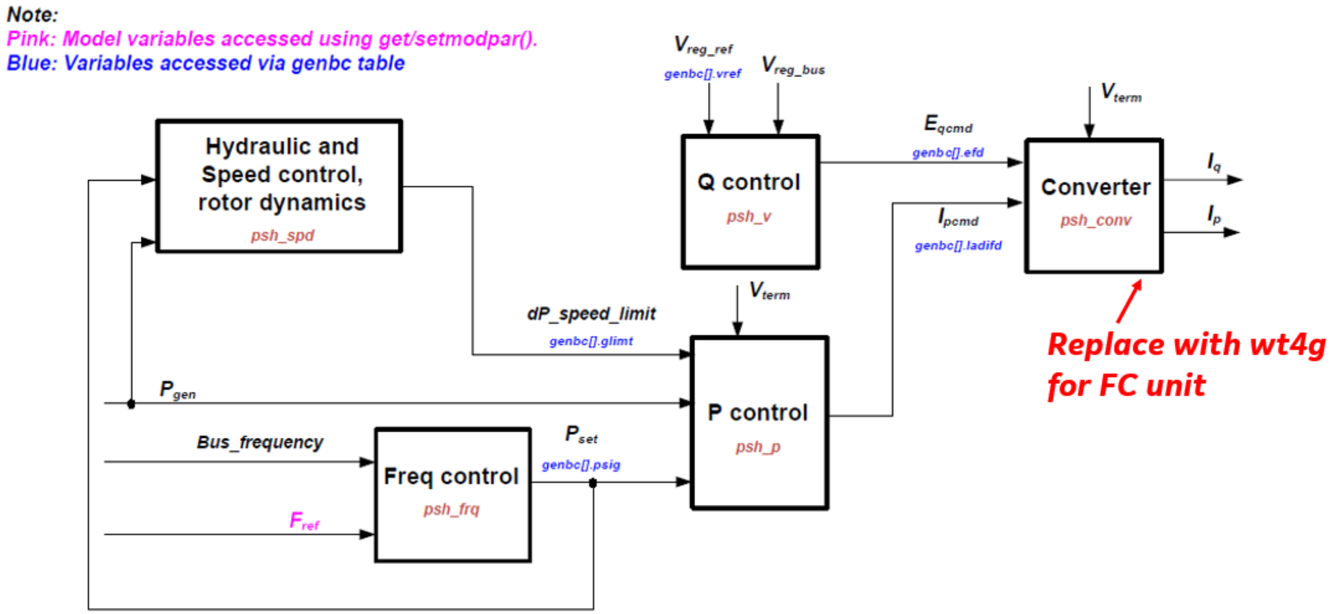
- Up to $202M/$64M reduction in Production Cost
- Up to 1.82/0.5 million tons of CO2 reduction
- Significant reduction in peak cycling and curtailment reduction

PSH plant revenue:

- Highest revenue in high renewable and high gas scenarios
- Reduced by more competing storage and lower renewables

DYNAMIC MODELING: PSLF Models & Benchmarking

- Suite of models added to PSLF to represent variable speed pumped hydro storage units largely based on the models developed as part of a previous DoE project* with minor updates based on GE Hydro's Powerfactory model.
- Benchmarking done against previous DoE project's PSSE model and GE Hydro's Powerfactory model for small test cases
- Reference tests included:
  - Voltage
  - Frequency response
  - Active power
  - Generator loss events
  - Fault response



- Frequency and Fault response of models was ensured to be reasonable for a high renewable WECC case as well.

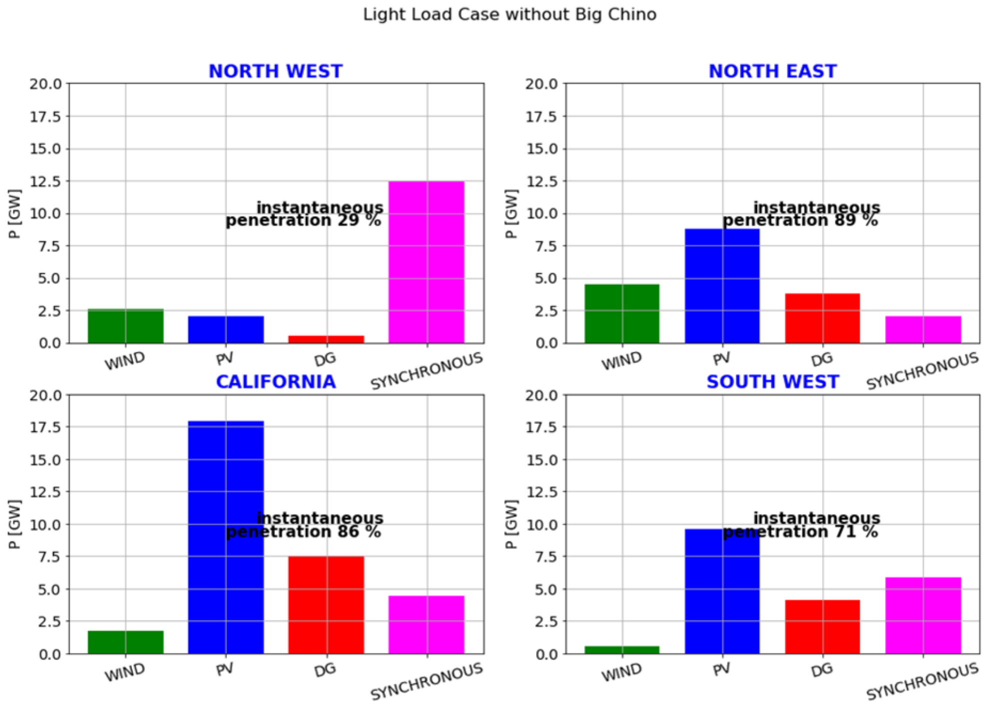
* https://ceeesa.es.anl.gov/projects/psh/psh.html

DYNAMIC MODELING: Assessment at Big Chino Set-Up

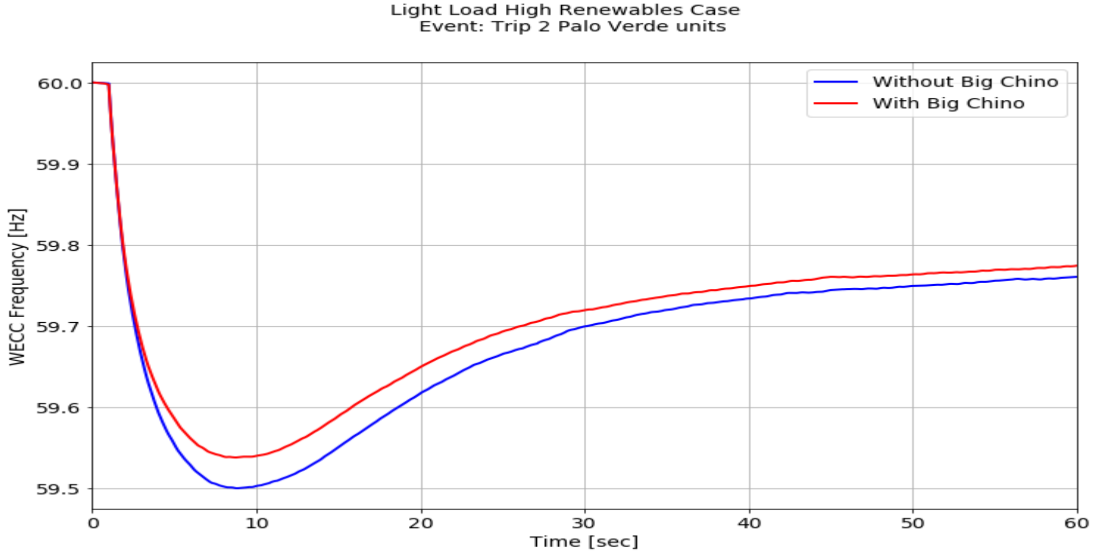
- All hours of the year from GE MAPS model filtered to select pinch points in frequency response capability
- The 2022 light load spring case load and generation were scaled to meet the average of these hours
  - MW outputs of generators scaled to meet MAPS area/unit type targets.
  - Loads scaled to meet the MAPS area loads

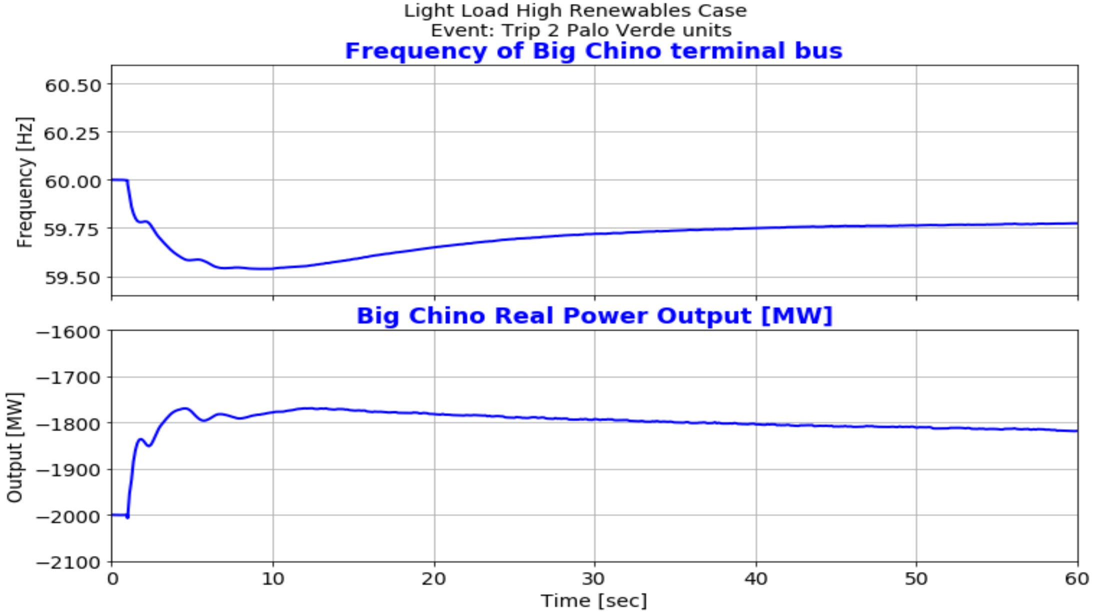
<u>GE MAPS Model Frequency Pinch Point Criteria</u>

- Spring
- between 10am and 3pm
- PSH Is pumping greater than 3000 MWh
- Wind + Solar generation > exceeds 60,000 MWh
- load is between 95,000 and 105,000 MWh
- Wind + Solar generation is 73% of load or more



DYNAMIC MODELING: Assessment at Big Chino Results





Frequency response margin and RoCoF without Big Chino

Area	FRO [MW/0.1Hz]	FR [MW/0.1Hz]	FR margin [MW/0.1Hz]	ROCOF (between 1 and 1.125s) [Hz/s]
WECC	858	**739.73**	**-118.27**	0.31
CALIFORNIA	261.53	42.22	-219.31	0.44
DESERT SOUTHWEST	146.04	**67.17**	**-78.87**	0.93
NORTHEAST	149.85	21.22	-128.63	0.27
NORTHWEST	146.81	347.82	201.015	0.08

Frequency response margin and RoCoF with Big Chino

Area	FRO [MW/0.1Hz]	FR [MW/0.1Hz]	FR margin [MW/0.1Hz]	ROCOF (between 1 and 1.125s) [Hz/s]
WECC	858	**814.18**	**-43.82**	0.31
CALIFORNIA	261.53	42.21	-219.32	0.43
DESERT SOUTHWEST	146.04	**145.50**	**-0.54**	0.91
NORTHEAST	149.85	20.46	-129.39	0.26
NORTHWEST	146.81	346.33	199.52	0.08

DYNAMIC MODELING: Additional Results

- Critical Interfaces: Big Chino plant has no measurable impact. Critical outages for these interfaces have no significant impact and the system is stable post-disturbance.

- Fault Response: For a nearby severe three-phase fault, the Big Chino plant:

  - Responds to arrest the voltage decline by increasing its reactive power output and reducing its pumping load.

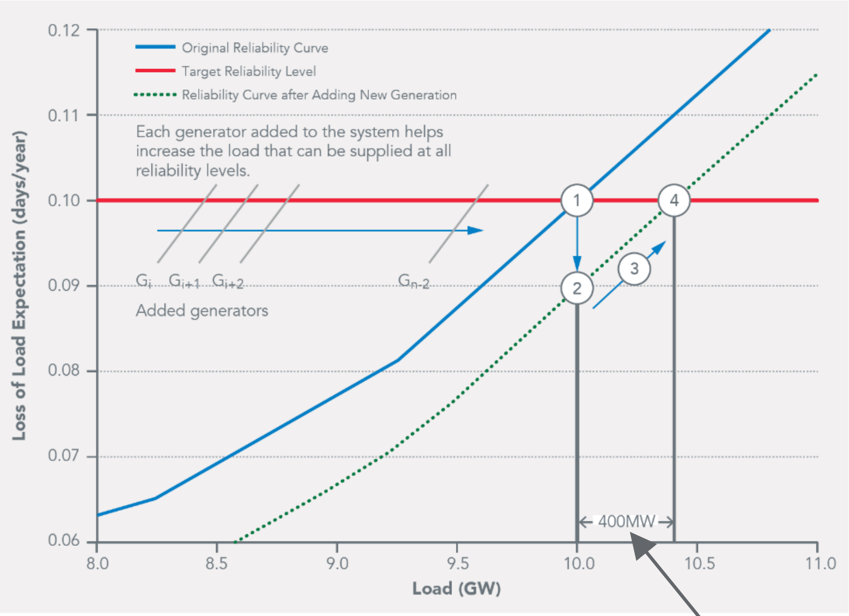
  - The terminal voltage in the case with Big Chino is higher than in the case without it having a slight positive impact on the system.

  - FSPSH gives greater reactive power contribution during the fault which is good, however once the fault is cleared its output oscillates for longer before settling. VSPSH settles after fault clearance much more quickly.

A Variable Speed PSH unit has a positive impact on grid frequency response and transient stability

CAPACITY VALUE: Approach

- Calculate capacity value of storage, for different ratios of energy/capacity (hours of storage)
- Simulations in GE MARS with same basic assumptions and PSH plants as production cost model
- Impact of wind/solar presence in the system to the capacity value
- Developed new GE MARS version which supports dynamic dispatch of storage
- Loss-of-load expectation (LOLE)-based analysis determined the effective load carrying capability (ELCC) of the incremental storage
- Capacity value is the resource's contribution towards meeting a reliability target.



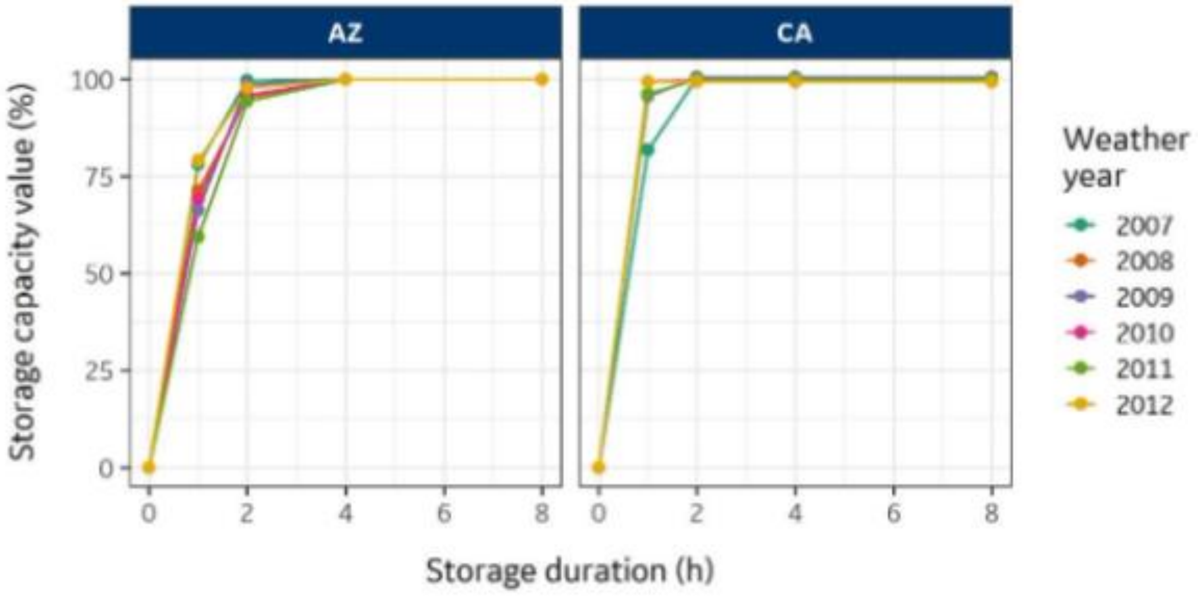
1. Initial system
2. Add resource, reliability improves
3. Increase load
4. Match initial reliability target

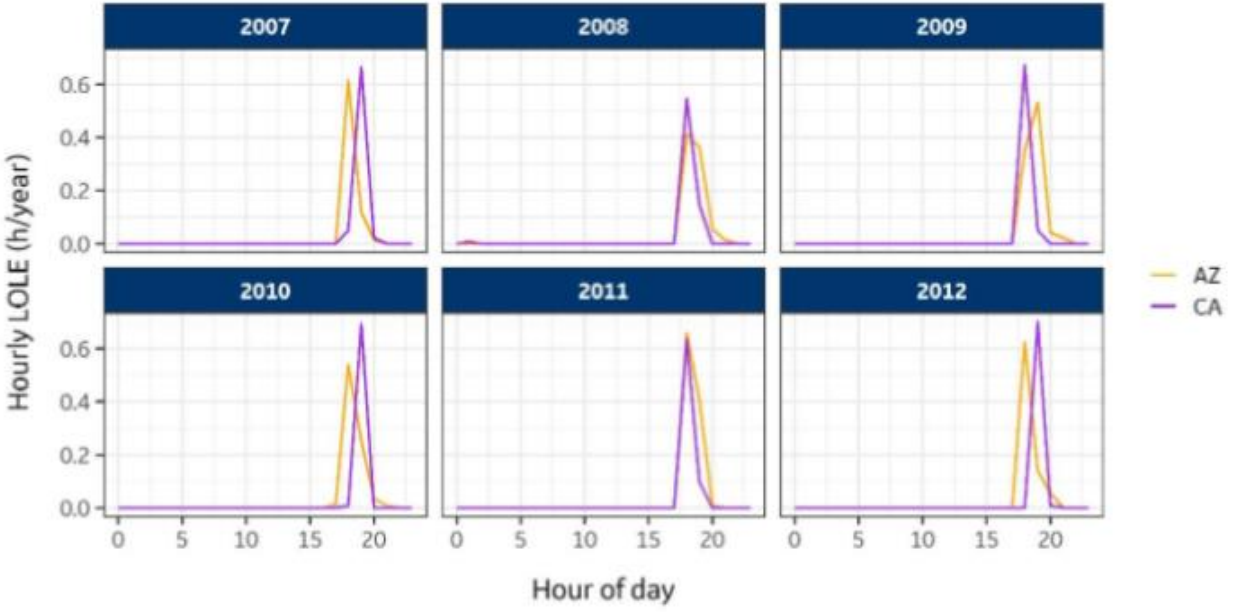
Capacity value

J. Katz, P. Denholm "Using Wind and Solar to Reliably Meet Electricity Demand, Greening the Grid" http://www.nrel.gov/docs/fy15osti/63038.pdf

CAPACITY VALUE: Base Case Results

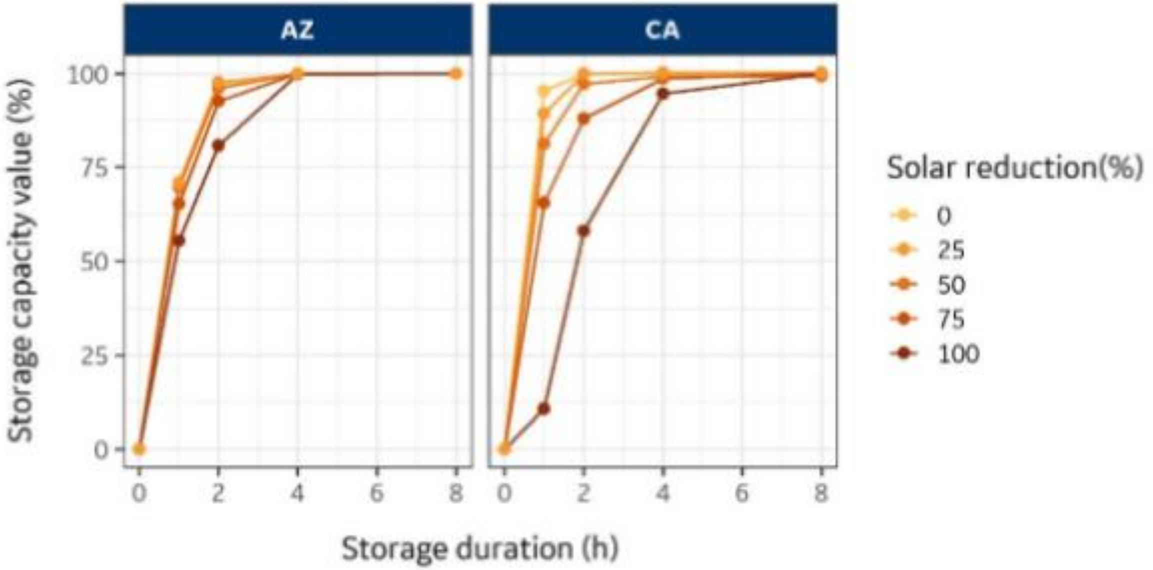
- Each ELCC calculation was done for 6 years of wind, solar, and load shapes (2007-2012), results are similar
- Results show Capacity Value as a % of nameplate capacity
- Base case results are above 95% with 2 hours of storage in AZ and with 1 hour of storage in CA
- High renewable penetration caused LOLE to be for periods of ~1 hour

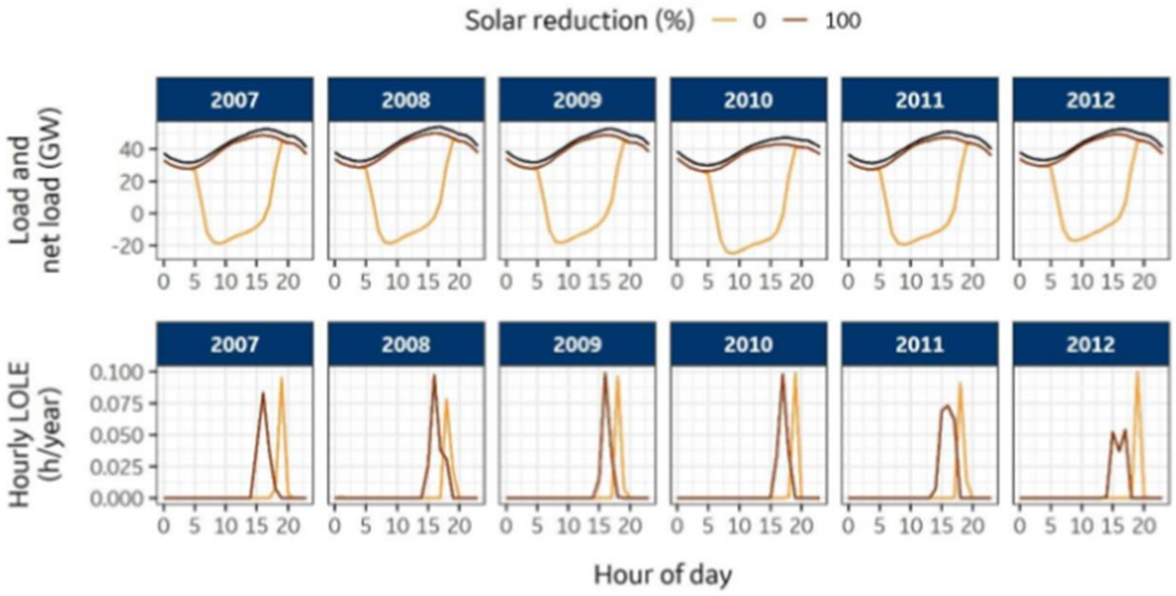




CAPACITY VALUE: Solar Reduction Sensitivities

- Reduction of solar in the system reduces the Capacity Value of PSH at lower storage durations
- Biggest effect shown in CA where PSH CV only reaches ~95% with 4 hours of storage with no solar in the system
- Reduction of solar removes the duck curve, makes risky hours spread across multiple hours, so 1 hour of storage is no longer sufficient to cover all the LOLE





As solar is taken out, PSH needs more storage duration to get to 100 CV

STUDY RESULTS AND CONCLUSIONS

- A **novel PSH Scheduling tool** was developed and for the first time incorporated the impact of variable height differences between reservoirs (‘head’) and variable speed machine behavior.
- **PSH has a positive impact** on reducing production cost, CO_2 emission and curtailment of other renewables in all scenarios even when competing with other storage.
- Two **new VSPSH stability models** have been created and incorporated into PSLF grid planning software so grid operators can assess their benefits.
- **Grid Resiliency**: A 2GW VSPSH plant in Arizona in *pumping mode* was able to markedly improve the frequency response by 50mHz in the US Western Interconnect.
- **Reserve Adequacy**: PSH has substantial capacity value even with short duration.
- Full report can be found at https://www.osti.gov/servlets/purl/1824300

PSH provides value to support power grid needs for generation adequacy, balancing, resiliency and stability.
New tools and methods are now available and being deployed to unlock that value.

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